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EDITED TRANSLATION

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DETERMINATION OF THE EFFECT OF ATMOSPHERIC HUMIDITY ON THE CHARACTERISTICS OF A TURBOFAN ENGINE.

B. D. Fishbeyn and N. V. Pervyshin

Designations

R — engine thrust,
C_R — specific fuel consumption,
n — number of rotor revolutions,
G_T — fuel consumption,
G_B — air consumption,
P — pressure,
T — temperature,
G_V — amount of air vapor in humid air,
$G_{B_{cool}}$ — amount of air involved in cooling the turbine,
R_r, R_B — gas constants of combustion products and dry air,
i — heat content,
H_u — net calorific value of fuel,
η_Z — combustion efficiency,
$\lambda_u = \frac{u}{a_{cr}}$ — coefficient of peripheral speed,
u — peripheral speed,
a_{cr} — critical speed of sound,
C_p — heat capacity at constant pressure,
k — adiabatic index,

$q(\lambda)=\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}}\cdot\left(1-\frac{k-1}{k+1}\lambda^2\right)^{\frac{1}{k-1}}\cdot\lambda$ — gas dynamic function,

d — moisture content (absolute humidity),

φ — relative humidity.

Ratios of the values for corresponding parameters at a different humidity to their values at $\varphi = 0$ are indicated by a bar overhead.

Indices

1 — engine inlet,

* — parameters of retarded flow,

0 — parameters reduced to conditions of standard atmosphere,

k — parameters behind the compressor,

Г, T — parameters in front of and behind the turbine,

s — parameters of the saturating vapors at a given T_H,

hum — humid air (gas),

H — ambient medium.

1. Introduction

The effect of atmospheric humidity on the basic parameters of jet engines has been discussed in literature.

It has been established that in the summer and autumn in the USSR and during the entire year in the tropics this effect can be quite noticeable; therefore, it should be taken into consideration when analyzing the characteristics of specific units and the engine as a whole.

Based on data from reference [1], we can assume that the adiabatic efficiency of the compressor and the turbine remains virtually the same; the force lines on the compressor characteristic, plotted in dimensionless form, are not displaced.

Engine parameters change only from variations in the properties of the working substance, namely, its gas constant and adiabatic index.

It usually requires a large amount of calculation and a long period of time to take the effect of humidity into account.

The method of calculation presented below for turbofan engines makes it possible to reduce considerably the time required while still preserving the accuracy necessary for practical use.

A diagram of the engine is shown in Fig. 1.

2. Basic allowances and relationships.

The following assumptions should be made when calculating the effect of humidity on the parameters of turbofan engines:

1) identical temperature for humid and dry air at engine inlet $T_1^* = \text{idem}$,

2) identical coefficient of peripheral speed,

3) identical geometry of gas-air tract,

4) self-similarity of all examined regimes of engine operation based on the Reynolds number.

In accordance with this, the following is valid when the engine operates in humid air:

reduced number of rotor revolutions —

$$(n_0)_{hum} = n_0 \frac{\sqrt{\frac{k_{hum}}{k_{hum}+1}}}{\sqrt{\frac{k}{k+1}}} \cdot \frac{\sqrt{R_{hum}}}{\sqrt{R_0}}, \tag{1}$$

reduced air consumption —

$$(G_{s_0})_{hum} = G_{s_0} \frac{\sqrt{k_{hum}\left(\frac{2}{k_{hum}+1}\right)^{\frac{k_{hum}+1}{k_{hum}-1}}}}{\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \cdot \frac{q(\lambda)_{hum}}{q(\lambda)} \cdot \frac{\sqrt{R_0}}{\sqrt{R_{hum}}}.$$

When k varies within the range 1.4 — 1.32, which corresponds to T_H = 288 — 323°K and φ = 0.0 — 1.0, the ratio $\frac{q(\lambda)_{hum}}{q(\lambda)} \approx 1.0$ with sufficient accuracy (errors does not exceed approximately 0.1 — 0.15%).

Then

$$(G_{a})_{hum} = G_{a} \cdot \frac{m_{hum}}{m} \cdot \frac{\sqrt{R_a}}{\sqrt{R}}, \tag{2}$$

where

$$m = \sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}.$$

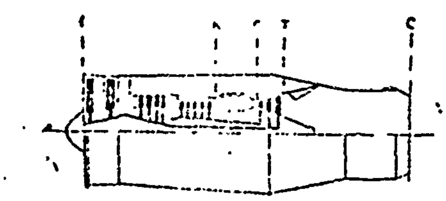

Fig. 1.

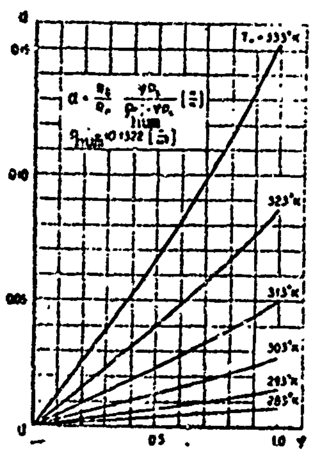

Fig. 2.

The values of the physical characteristics of humid air are determined with the known formulas of thermodynamics for a gaseous mixture [2] – [4]:

absolute moisture content –

$$d = \frac{R_a}{R_v} \cdot \frac{\varphi p_s}{p_{hum} - \varphi p_s} \tag{3}$$

(the dependence of d on φ and T_H is presented in Fig. 2),

heat capacity of the mixture —

$$C_{p_{\text{hum}}} = \frac{C_{p_{\text{a (gas)}}} + dC_{p_{\text{v}}}}{1+d}, \tag{4}$$

gas constant of the mixture —

$$R_{\text{hum}} = \frac{R_{\text{a (gas)}} + dR_{\text{v}}}{1+d}, \tag{5}$$

adiabatic index for the mixture —

$$k_{\text{hum}} = \frac{C_{p_{\text{hum}}}}{C_{p_{\text{hum}}} - R_{\text{hum}}}. \tag{6}$$

When calculating the processes of compression and expansion, heat capacity and adiabatic indices are taken for the mean temperatures of these processes.

Fuel consumption through the combustion chamber is found from the heat-balance equation

$$G_{\text{T}} = \frac{\dfrac{(G_{\text{a}} - G_{\text{a cool}})_{\text{hum}}}{1+d} + G_{\text{v}} \dfrac{C_{p\text{v av}}^{T_{\Gamma}^{*}} T_{\Gamma}^{*} - C_{p\text{v av}}^{T_{\text{K}}^{*}} T_{\text{K}}^{*}}{i_{\Gamma}^{*} - i_{\text{K}}^{*}}}{\dfrac{H_{\text{u}} \cdot \eta_{\Gamma}}{i_{\Gamma}^{*} - i_{\text{K}}^{*}} - 1}, \tag{7}$$

where $C_{\text{pv av}}^{T_{\text{K}}^{*}}$, $C_{\text{pv av}}^{T_{\Gamma}^{*}}$ are the average heat capacities of the vapor at constant pressure, taken at temperatures T_{K}^{*}, T_{Γ}^{*}.

Since turbine performance curves are usually plotted for combustion products in dry air, when using them in this case, we must consider the presence of water vapor:

$$\left(\frac{n}{\sqrt{T_{\Gamma}^{*}}}\right)_{perf} = \left(\frac{n}{\sqrt{T_{\Gamma}^{*}}}\right)_{hum} \cdot \frac{\sqrt{R_{\Gamma}\frac{k_{\Gamma}}{k_{\Gamma}+1}}}{\sqrt{R_{hum}\frac{k_{hum}}{k_{hum}+1}}}, \tag{8}$$

$$(G_{B} + G_{T})_{hum} = (G_{B} + G_{T})\, \frac{m_{hum} \cdot q(\lambda)_{hum} \cdot \sqrt{R_{\Gamma}}}{m \cdot q(\lambda) \cdot \sqrt{R_{hum}}}. \tag{9}$$

here

$$m = \sqrt{k_{\Gamma}\left(\frac{2}{k_{\Gamma}+1}\right)^{\frac{k_{\Gamma}+1}{k_{\Gamma}-1}}},$$

where $\frac{q(\lambda)}{q(\lambda)_{hum}} \approx 1.0$ for the possib.. range $k = f(\varphi, T_{\Gamma}^{*})$.

Compression and expansion are calculated with the well known equations used in the theory of gas turbine engines [5].

The position of points, showing the joint operation of engine units, on their performance curves is found by the method of successive approximations while satisfying the equation of continuity in all sections of the gas-air tract and fulfilling an energy balance.

In other respects, the calculation methodology which takes into account air humidity does not differ from the usual methods applied in the theory of gas-turbine engines.

When designing two-contour engines with displacement of the flows of the internal and external contours, we assume that static pressure in the sections at the mixing chamber inlet is identical for both contours. Parameters at the end of the mixing chamber are found from the equations of gas flow in a cylindrical tube.

Based on this method we can determine the effect of humidity in a wide ambient temperature range under various control programs.

The results of calculations based on the effect of humidity on the parameters of an engine with flow displacement, conducted at $T_H = 288 - 333^{o}K$ and $\varphi = 0 - 1.0$ for engine operations from 0.4 nominal to take-off performance, have shown that when the following is observed at engine inlet

$$T_1^* = \text{idem}, \quad \lambda_c = \frac{u}{a_{cr}} = \text{idem}$$

we can represent the variations in the basic parameters in the form of generalized relationships which are valid throughout the examined range of T_H and φ:

$$\begin{aligned} \bar{R}_0 &= 1 + a_1 \cdot d + b_1 \cdot d^2, \\ \bar{G}_{T_0} &= 1 + a_2 \cdot d + b_2 \cdot d^2, \\ \bar{G}_{B_0} &= 1 + a_3 \cdot d + b_3 \cdot d^2, \\ \bar{n}_0 &= 1 + a_4 \cdot d + b_4 \cdot d^2, \\ \bar{T}^*_{\Gamma_0} &= 1 + a_5 \cdot d + b_5 \cdot d^2, \end{aligned} \tag{10}$$

where d = absolute humidity. These relationships (10) are represented in Figs. 3 and 4.

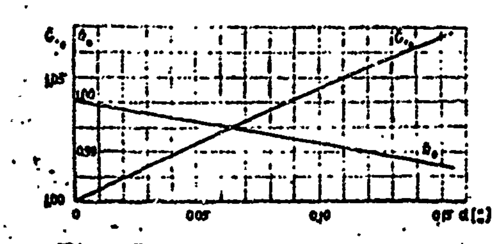

Fig. 3.

For a turbofan engine with a full displacement and the degree of its two-contour characteristic ~ 1.0, the following values for coefficients a and b are obtained:

$$a_1 = -0.0826, \; a_2 = 0.4882, \; a_3 = -0.3352, \; a_4 = 0.2607, \; a_5 = -0.0845,$$
$$b_1 = -0.0021, \; b_2 = 0.3828, \; b_3 = -0.4011, \; b_4 = -0.1538, \; b_5 = -0.119$$

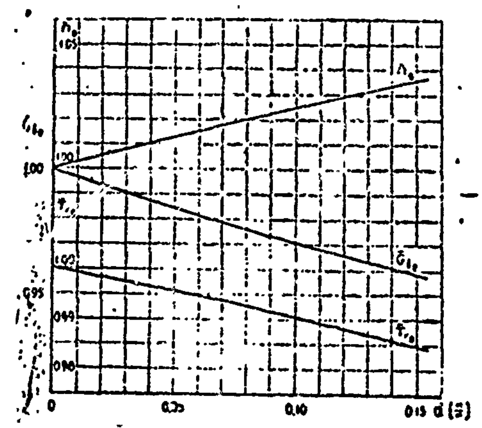

Fig. 4.

Thus, when studying the effect of humidity on engine parameters, it is not necessary to perform numerous and time-consuming calculations.

The method suggested was used in the evaluation of the effect of humidity on parameters of turbofan engines with 0 – 4 degrees, of a two-contour nature, flow displacement, and a separate exhaust in the range gas temperatures in front of the turbine $T_{\Gamma}^{*} = 900 - 1400^{\circ}$ abs.

The calculations showed that the numerical values indicated for coefficients a and b allow the computation of relative parameters with respect to (10) with an error no greater than 0.5% for the entire range of T_{Γ}^{*} and degrees of the two-contours characteristics for the designs of turbofan engines studied.

To achieve the greatest accuracy in determining relative parameters, we should correct the values for coefficients a and b in equations (10) (Figs. 3 and 4). For this it is necessary to perform two or three calculations with different values for absolute humidity d and use the derived relationships:

$$\bar{G}_{\text{в}_0},\ \bar{R}_0,\ \bar{G}_{\text{т}_0},\ \bar{n}_0,\ \bar{T}_{\Gamma_0}^{*} = f(d).$$

Generalized relationships of the type (10) make it possible to plot the throttle characteristics for any φ and T_H, based on available engine throttle characteristics calculated for dry-air operation, and then to study the quantitative effect of humidity under any principle of engine control in the examined conditions.

As a result of such a study, graphs are plotted showing the effect of humidity on thrust, specific fuel consumption, and other parameters, as presented in Figs. 5 and 6.

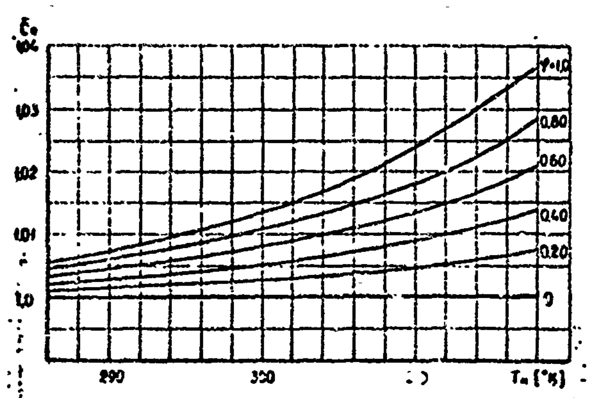

Fig. 5.

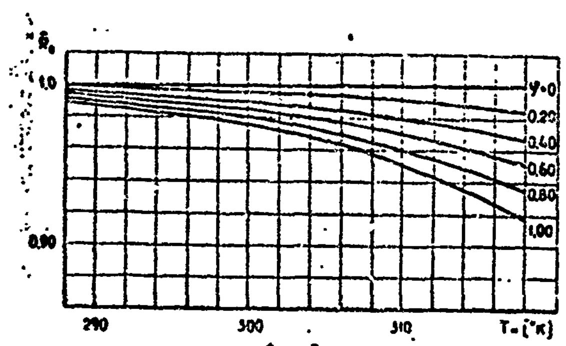

Fig. 6.

The graphs in Figs. 3 and 4 are used in the following manner. The value of absolute humidity d based on formula (3) is found for given T_H and φ. Then with the aid of Figs. 3 and 4, based on the obtained value of d, $\bar{F}_0$, $\bar{G}_{T_0}$, G_{B_0}, n_0, $T^*_{\Gamma_0}$ are determined and multiplied by the value of the corresponding parameters taken from the

throttle performance curve of the engine and standard conditions. The stratification of the throttle performance curve (for example, for engine thrust) due to the effect of humidity is shown in Fig. 7.

We should emphasize that this method and the generalized relationships (10) can be recommended for the study of the humidity effect on parameters of any gas-turbine engine.

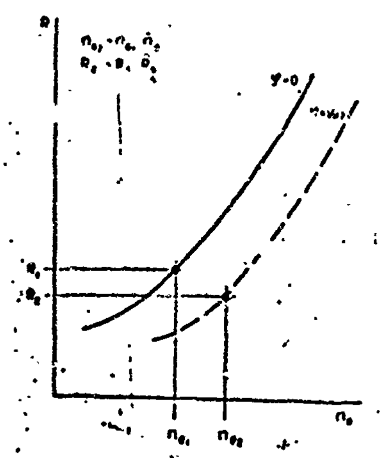

Fig. 7.

3. Conclusions

1. Generalized relationships are derived for $\overline{R}_0$, $\overline{G}_{T_0}$, G_{B_0}, n_0, $T^*_0 = f(d)$, which make it possible to evaluate easily the effect of humidity on the basic parameters of a turbofan engine.

2. This method can be recommended for use in the study of any type of gas-turbine jet engine.

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